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Managing Deficit Irrigation

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At the time of this writing California is experiencing a record breaking drought that poses serious problems for irrigated agriculture, with some farms paying extraordinary spot prices for water or taking land out of production altogether. Such water shortages are shaping the future of irrigated agriculture, not only in California but in much of the rest of the world as well. In addition to escalating competition for water in an increasingly water-short world, irrigators today also face converging pressures of energy costs, environmental impacts and food security. The value of water and the costs of irrigation are increasing rapidly, and that is causing many farms to shift from *full irrigation*, the conventional norm which seeks to maximize crop yield per unit of land, to deliberate under-irrigation of crops - *deficit irrigation* - to maximize net economic returns to water (*English, et als, 2002*). Also known as regulated deficit irrigation (RDI) or partial irrigation, it is a profitable strategy when water supplies are limited or expensive

Deficit irrigation requires much more sophisticated management, and that entails greater analytical effort. Relatively few farms are equipped to deal with it effectively. A new generation of management technology is needed, particularly new analytical tools for helping irrigators decide when and how to allocate limited water among different fields to best effect. The challenges of building and using a decision support system for deficit irrigation management are the subject of this paper[3].

Deficit irrigation -- optimal irrigation

The rationale for deficit irrigation is illustrated by Figure 1 which summarizes an observed relationship between applied water and crop yield for winter wheat in the Columbia Basin. The data points represent irrigation applications that ranged from 28% to 100% of full irrigation. As indicated, the marginal yields at the highest levels of irrigation were small; for example, the last 20% of applied water produced only 4% of the yield. Similar findings have been reported for many other crops in other areas of the country and other regions of the world.

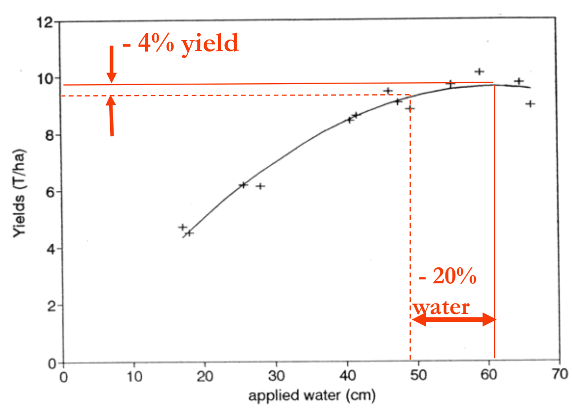

Figure 1: applied water vs crop yields; winter wheat in the Columbia Basin (from: English and Nakamura, 1989)

The logic of deficit irrigation is based on three questions; (i) what does it cost to apply the last increment of water; (ii) would the revenue from the last increment of yield produced be greater than the

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[3] A team at Oregon State University, the University of California, Washington State University and NRCS have developed such a decision support system for optimum irrigation management. The insights and accomplishments from that effort inform this section of the paper.

incremental cost of the water; and (iii) might that last increment of water be worth more if used on other crops or sold off-farm? In the example in Figure 1 the economic optimum level of water use was found to be 16% less than full irrigation.

Conventional *vs* deficit irrigation management

Conventional irrigation management typically involves monitoring soil moisture in the drier parts of a field and irrigating as needed to avoid crop stress that would reduce yield or quality. Common management practice also incorporates a margin for error, compensating for the uncertainty of soil moisture conditions by irrigating early, before stress occurs, and compensating for spatial variability by over-irrigating much of the field to insure adequate water for the entire field (*Hillyer and Robinson, 2010; English, 2010*).

Deficit irrigation management involves under-irrigating most or all of a field at some times. Rather than avoiding crop water stress irrigators *control* stress at levels that can increase profits. And the allowable margin for error must be minimized because that reduces the returns to water. This level of management is far more challenging than conventional irrigation, requiring a more complete understanding of the disposition of applied water, the patterns of crop water availability in a field and crop physiological responses to available water (*Sadler, et als, 2005*) . To manage at that level, individual farmers need a higher level of technical support than is routinely available today.

The following paragraph outlines the analytical capabilities needed for optimum irrigation management and summarizes the general features of an integrated set of analytical tools – a decision support system (DSS) – designed for analysis, evaluation and implementation of optimum irrigation strategies. The concepts involved are illustrated with an existing prototype system known as *Irrigation management online*, or IMO (*Hillyer and Sayde, 2010*).

DSS Design challenges and IMO

Researchers developing a prototype decision support system for optimal irrigation management have identified three primary challenges (*English and Evans, 2013*):

- *Fully engaging the user* as a direct participant in the analytical process in order to adequately represent the user's objectives, experience and constraints.
- *Retaining analytical complexity* in order to accurately represent the physical system … the soil, climate, crop, water supply and irrigation system involved.
- *Streamlining the computational process* in order to facilitate fast and efficient analysis of alternative irrigation strategies;

The following paragraphs detail the problems posed by these challenges, and discuss ways they have been addressed by a prototype decision support system known as *irrigation Management Online* (IMO) that incorporates sophisticated analytical and decision support capabilities not found in conventional irrigation decision support software (*Robinson, 2009*).

User engagement

What 'optimum' means depends upon the goals, preferences and circumstances faced by individual farm managers. Researchers have derived optimization techniques using purely objective mathematical procedures, such as linear programming, genetic algorithms and so on. However this approach requires first establishing an objective function, and the objectives and preferences of individual farm managers and the constraints under which they operate are variable and difficult to capture and quantify (*English and Orlob, 1978; English, et sl. 2002).* IMO therefore uses a guided search procedure, relying on farm managers to direct an iterative analysis of irrigation strategies. By doing so the managers' individual experience, preferences and awareness of the specific circumstances of their individual farms are built into the analytical procedure.

Retaining analytical complexity

Optimum management of deficit irrigation requires realistically modeling the complex chain of relationships between applied water and crop yield. It is a daunting analytical task. Crop yields depend upon the timing and amount of crop water availability in relation to crop physiological development. To evaluate crop water availability on a field scale requires increased spatial resolution of available water (*Sadler et al., 2005; English, 2010*). The analyst must therefore consider the timing and uniformity of applied water, spatially variable soil characteristics, surface water redistribution, soil water dynamics, crop canopy and rooting pattern development *throughout* the field. The analyst must then model the physiological responses of the crop to water availability and weather-driven potential crop water uptake over the course of a season. The analysis must be integrated over the entire field to estimate total yields. Irrigation system constraints (timing and amount of available water, delivery system capacity, and operational restrictions) must also be considered to ascertain the feasibility of a strategy.

Conventional irrigation management minimizes this analytical burden by making certain simplifying assumptions. For example, the difficulty of modeling spatial patterns of crop water availability is reduced to a minimum by managing for field average, or 'low quarter' soil moisture conditions and making *a priori* estimates of application efficiencies as a way of generalizing the spatial disposition of applied water and the variability in soils (*Hillyer and Robinson; 2010*). Similarly, if a field is fully irrigated the analyst can assume maximum potential yields, rather than explicitly modeling crop water stress and its effects on crop yield.

While these simplifying assumptions are generally reasonable for full irrigation under normal field conditions, they can fatally compromise an analysis of alternative irrigation strategies that involve partial irrigation. It is therefore necessary that analytical models represent the complexity of the system.

Desirable capabilities of decision support system to facilitate effective management of deficit irrigation include (*Hillyer and Robinson, 2010*):

- *Modeling application efficiencies*: in conventional practice, application efficiencies are normally assumed *a priori*. However, because application efficiency varies with irrigation intensity the ultimate disposition of applied water must be explicitly analyzed when water use is less than full irrigation.
- *Modeling crop yields*: development of science-based models of this relationship is a particular challenge, since they must achieve model accuracy using input parameters that can be readily determined on a field scale.
- *Conjunctive irrigation scheduling:* optimal allocation of limited water among multiple fields requires simultaneous scheduling of irrigations for all fields that share a common source of water, rather than scheduling each field independently.
- *Long range (full season) forecasting of crop water requirements:* longer range forecasting of irrigation requirements enables managers to better anticipate when irrigation demands will exceed delivery system capacities, providing more time and flexibility to modify irrigation schedules.
- *Comprehensive economic analysis:* the analysis must estimate resource use (energy, water, labor, capital investment) to determine the costs of an irrigation strategy. When water supplies are limited the analyst must also consider the value of water used for alternative purposes. For example, by reducing irrigation on one field, the water saved might be used more profitably on another field or sold on the spot market.

- *Feedback:* field data collected during the season can be used to update and adjust expected irrigation requirements, and for iterative recalibration throughout the growing season to develop a more precise and robust analytical engine.

Streamlining the computational process

Limiting the computational burden is another primary challenge. The extensive analytical effort outlined above may need to be repeated many times to adequately evaluate alternative strategies for multiple scenarios. Imagine, for example, a grower who is considering six alternative strategies for irrigating four crops with a limited amount of water. He wants to evaluate outcomes for wet, average and dry weather years. His water allotment for the coming year is uncertain but might be 70%, 80% or 90% of normal. The analysis may need to be replicated at 20 hypothetical points in the field to adequately represent the non-uniformity of applied water and spatial variability of field soils. The search for an optimum water use plan in this case would then require 4,300 individual simulation runs. Additionally, as weather, water supplies and other factors change during the season the manager may need to repeat some elements of the analysis frequently.

The IMO development team has invested heavily in advanced modeling techniques to maximize the analytical power and the computational efficiency of the analytical engine, balancing the developmental effort and computational burden with the analytical power and precision. Key features include:

- multi-variable Monte Carlo simulation to represent interacting variables including irrigation uniformity, the spatial variability of soil parameters and the uncertainties of crop root zones;
- an algorithm for continuously adjusting the computational time-step as needed to match the sensitivity of simulations to the time-step used in modeling;
- efficient mathematical representations of non-linear components;
- an efficient coding language, and efficient incorporation of all computational modules as embedded code to minimize run time dependencies (*Hillyer, et al., 2003*).

Using IMO

Pilot applications of the IMO decision support system have yielded valuable general perspectives:

1. IMO will be particularly useful for managers facing significant water shortages or high irrigation costs, who therefore need to develop unconventional, partial irrigation strategies.
2. Formulation of optimum irrigation strategies depends upon reliable crop yield models derived from rigorous experimentation and high quality field data. Effective use of IMO therefore requires partnering with research and extension professionals with local research and production experience who can provide general guidelines for deficit irrigation strategies. IMO can then be used to evaluate potential outcomes of those strategies and develop case specific operational plans for implementing the strategies of choice.
3. Optimal allocation of limited water among multiple fields requires simultaneous scheduling of irrigations for all fields that share a common water source, rather than independent scheduling of each field.
4. Dissemination of IMO will require trained intermediate service providers, e.g. commercial scheduling services or a new generation of mobile labs focused on advanced irrigation management, to market the system and provide technical support for field operations and user interpretation of outputs. These service providers would use IMO to prescribe seasonal irrigation schedules for implementing a desired irrigation strategy, track and document field conditions and irrigation history and update the schedule as the season progresses.
5. User adoption and use of IMO should involve *gradually* increasing investment of time and effort. An initial formulation of general management plans based on default parameters could first engage the

user and demonstrate the utility of the system. As the user becomes more familiar with IMO and more engaged in using it they can proceed to higher levels of refinement at the pace they choose.

6. IMO can also be used for design, strategic planning and policy development, for example for energy use analysis (funded by by BPA) and risk management (funded by RMA). Such applications can be extended to other agencies (DWR), irrigation districts and large corporate farms.

References

English, M., and R. Evans. 2013. *A Road Map for Energy and Water Efficiency in Irrigated Agriculture; guiding principles for transforming the market*. Final report for: Northwest Energy Efficiency Alliance, Portland, Oregon.

English, M. J. 2010. *A developing crisis in irrigation advisory services*; ASABE-IA 5th Decennial International Irrigation Conference, Phoenix, December.

English, M.J., Solomon, K. H., and Hoffman, G.J. 2002. "A paradigm shift in irrigation management." Jubilee Year Edition (invited paper) , *J. Irrigation and Drainage Engineering*, ASCE. Vol. 28, No 5.

English, M.J. and B. Nakamura. 1989. Effects of deficit irrigation and irrigation frequency on wheat yields. Journal of irrigation and drainage engineering, American Society of Civil Engineers. 115(2):172-184.

English, M.J. and G.T. Orlob. 1978. Decision Theory and Irrigation Optimization, California Water Resources Center Contribution No. 174.

Hillyer, Charles, and C. Sayde. 2010. *A Web Based Advisory Service For Optimum Irrigation Management.* ASABE-IA 5th Decennial International Irrigation Conference, Phoenix, December.

Hillyer, C. and P. Robinson, 2010. *Envisioning The Next Generation Of Irrigation Schedulers*; ASABE-IA 5th Decennial International Irrigation Conference, Phoenix, Dec. 2010

Hillyer, C.H. Bolte, J., van Evert, F. Lamaker, A. 2003. The ModCom modular simulation system. *European Journal of Agronomy* 18: 333 – 343.

Isbell, B. M. 2005. An Irrigation Efficiency Model for Optimum Irrigation Management. MS Thesis. Corvallis, Oregon. Oregon State University, Department of Bioengineering.

Robinson, P. M. 2009. The Next Generation of Irrigation Management Programs. World Environmental and Water Resources Congress 2009: pp. 1-9.

Sadler, E. J., R. G. Evans, K. C. Stone, and C. R. Camp. 2005. Opportunities for conservation with precision irrigation. *JOURNAL OF SOIL AND WATER CONSERVATION*60(6): 371-379.

Example: optimum water use for alfalfa on a Columbia Basin farm

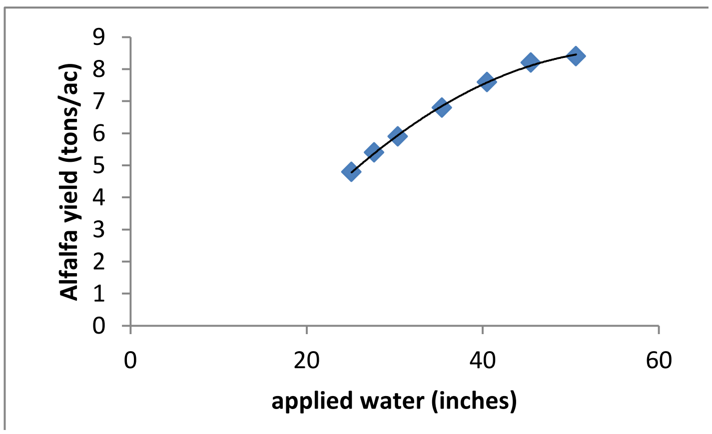
Seven irrigation strategies, involving levels of water use ranging from 50% to 100% of full irrigation, were analyzed. The relationship between applied water and alfalfa yield shown in the table and graphical production function below was generated using IMO. Maximum yield requires 50.6 inches of water, but the highest net profit per unit of water corresponds to 27.7 inches of water, or 55% of full irrigation. Since water conserved by partial irrigation can be profitably used on other fields of the same crop, maximizing returns to limited water will maximize net farm income. The preferred strategy is therefore to maximize net returns to water by applying 27.7 inches, yielding 5.4 tons per acre.

Applied water (inches)	Crop yield (tons/ac)	Revenue ($/ac)	Energy Cost ($/ac)	Haying costs ($/ac)	Net income ($/ac)	Net returns to water ($/ac-in)
50.6	8.4	1848	342	353	1,154	22.8
45.5	8.2	1804	307	344	1,152	25.3
40.5	7.6	1672	273	319	1,079	26.7
35.4	6.8	1496	239	286	971	27.4
30.4	5.9	1298	205	248	845	27.8
27.7	5.4	1188	187	227	774	28
25.1	4.8	1056	169	202	685	27.3

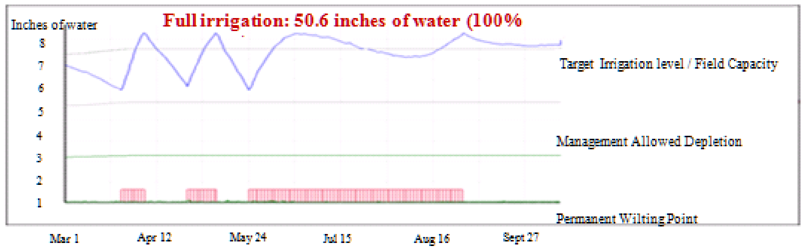
Yield Response

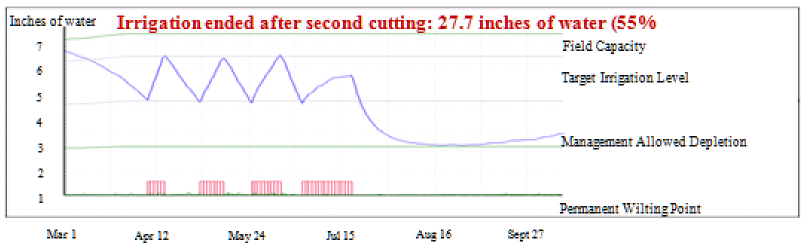
Water (in)	Yield (T/acres)
50.6	8.4
45.5	8.2
40.5	7.6
35.4	6.8
30.4	5.9
27.7	5.4
25.1	4.8

Production Curve



The irrigation manager, having established the preferred irrigation strategy, can then use IMO to generate projected seasonal irrigation schedules to implement that strategy, along with expected soil moisture profiles for the season. The graphs below show seasonal forecasts for the full irrigation strategy (50.6 inches) and the preferred deficit irrigation strategy (27.7 inches). The irrigation dates are indicated in red, the projected soil moisture is indicated by the blue curve.





A scheduling service provider can use the seasonal plan as a prescription for in-season irrigation scheduling. However, given the variability of seasonal weather, the likelihood of departures from planned irrigation schedules and the uncertainies in modeling field-wide soil moisture conditions it is virtually certain that the initial seasonal irrigation plan generated for a specific field will need to be revised periodically. Field data collected by a scheduling service is therefore used to tune the models to match the actual field conditions, gradually recalibrating the model parameters involved. As the season progresses the plan is updated to account for actual weather conditions, irrigation activities and corrected soil moisture estimates based on field measurements.

Figures A and B illustrate a pre-season plan and a mid-season updated plan for another Columbia Basin farm, also involving alfalfa.

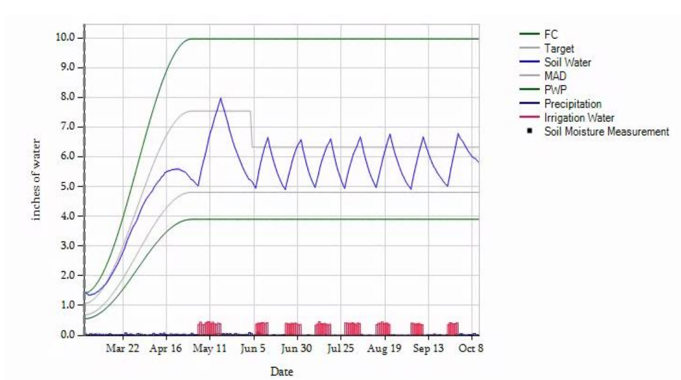


Figure A
Pre-season irrigation plan

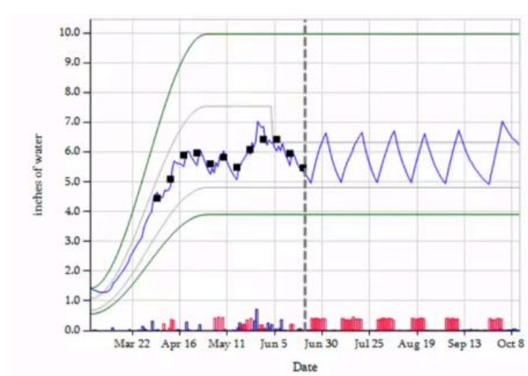


Figure B
Updated plan as of June 20

Analyses such as shown above, generated for multiple crops and fields, can be used as building blocks to establish a full-farm forecast of total farm water requirements for an entire upcoming season, allowing the manager to visualize and analyze total water use, anticipate when water demands will exceed farm water delivery capacity and adjust agronomic schedules accordingly.